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On the use of macro synthetic fibres in precast tunnel segments

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1. Summary

The effectiveness of tunnel segments reinforced with 12 kg/m^3 polymeric macro-fibres in addition to a minimum steel reinforcement ratio has been assessed. Precast tunnel segments have been adopted to test this fibre-reinforced solutions for structural elements, in which the longitudinal reinforcement has been designed to comply only with EC2 minimum reinforcement requirements for no seismic design situations. This experimental campaign is the final step of a wider research, aimed at investigating an optimized mixture for the use of the polymeric fibres ISTRICE, as well as investigating the performance of some structural elements such as slabs, beams and tunnel segments, which are produced by using such a mix design.

The experimental programme has been devised in such a way that in a first stage the structural behaviour of a fibre-reinforced tunnel segment has been first of all investigated under a 3 point bending test at 7 days after casting, mainly to underline the behaviour that this element would have in an initial movement phase. In a second stage the effectiveness of the fibre reinforced solution has been checked testing the tunnel segment under a lateral compression at 28 days, to highlight the behaviour of the element during the assembly stage with the advancing of the TBM.

The results, analysed in terms of maximum load bearing capacity and crack openings highlight the effectiveness of the proposed structural polymeric fibre-reinforced concrete combined with a minimum steel reinforcement solution, which, also in view of their easiness of execution and reduced invasiveness, can stand as a reliable alternative to traditional reinforced tunnel segments.

2. Introduction

Underground structures and in particular tunnels are taking a strategic role in transport in countries with high population density, but also in developing countries to facilitate the distribution of resources. Their construction for the purpose of traffic management in the underground, such as railway tunnels, roads and subways, or to provide other services, such as pipes for water supply or hydropower and sanitation, is an important aspect of civil and world economy.

The construction process, which involves in many cases the prefabrication of segments joined to ring put in place with the aid of TBM (Tunnel Boring Machine, [1,2]) technology, has been operating for several years as a process of gradual optimization ([3], [7]) in an attempt to proceed at maximum industrialization and to exploit the boundary conditions of the work which provide a favourable axial action due to the confinement of the land and, in particular for the water conduits, the limited size of the segments, and therefore a limited state of bending.

In this context, a very interesting design solution is to reduce the amount of traditional reinforcement to a minimum reinforcement disposed along the ring to respond to the longitudinal bending of the segment [03, 06], and to eliminate any other type of reinforcement by making use of a fibre-reinforced concrete with metallic fibres or, in the specific case of the tunnel water, here considered, polymeric fibres, which are very effective up to high values of crack opening also relevant, namely of the order of 3 mm. In this paper, the investigation of a tunnel reinforced with 12 kg/m^3 of polypropylene structural fibres ISTRICE 39mm long with a diameter of 0.78m is presented.

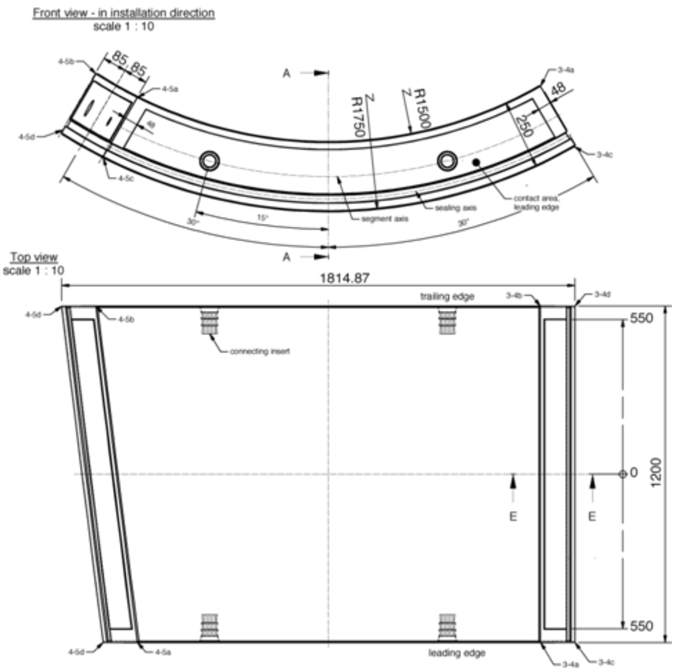

Fig. 1 *Front and top view of the tunnel segment investigated.*

Table 1 *Geometry features*

Geometry	
Shape [-]	Trapezioidal
Width [mm]	1200
Thickness [mm]	250
Average length [mm]	1700
Inner radius [mm]	1500
Reinforcement	
Steel reinforcement [-]	6+6□ı2 - (B450 C)
Fibre reinforcement [-]	12 kg/m^3 polymeric fibers (ISTRICE iBeton 39/0.78)

Table 2 *Mix design of fiber-reinforced mixture with the addition of blast furnace slag (L)*

w/c ratio	0.47
Cement CEM I 52.5 [kg/m^3]	340
Blas furnace [kg/m^3]	60
Sieved sand 0/3 [kg/m^3]	620
Natural sand 0/12 [kg/m^3]	440
Round gravel 8/15 [kg/m^3]	710
Acrylic superplasticizer [kg/m^3]	5.3
Fibres 39/0.78 [kg/m^3]	12
Total water [l/m^3]	207
SSD water [l/m^3]	188

* Mix 0.8 mc (31/07/2013) – workability S3 after 1h.
* Additive calculated on the total quantity of fine materials

The campaign is the final step of a wider research, aimed at investigating the performance of structural elements such as beams and slab and tunnel segments, realized through the use of the same mix design.

3. Experimental programme

Two different load tests were carried out on a FRC tunnel: a 3-point bending test after 7 days of curing, aimed mainly to highlight the behaviour that this element would have in an initial phase of movement (Figure 3); a compression test after 28 days, aimed at highlighting the behaviour of a tunnel subject to jacket pushing during the progress of the TBM in mounting conditions (Figure 5). The load tests were performed on precast segments of the tunnel characterized by the same geometry used for the construction of the tunnels hydroelectric plants Pando located in the province of Chiriqui in Panama. The tests were carried out on a segment which forms the lining of the tunnel and in particular on a second key segment of the ring, characterized by a trapezoidal shape and having a thickness of 250 mm, a width along the generating line of about 1200 mm and an average length, according to the development of the ring, of about 1700 mm (Figure 1 and Table 1). It is important to note that in the tunnel segment investigated any slot of the guide-bar and transverse connectors were considered, then the geometry deviates, for these details, from that of the segment originally shown in Figure 1.

In tunnel segments a minimum reinforcement was planned, equal to 6 + 6 ∅12 introduced in two lateral chords and reciprocally connected with 2 + 2∅8, as shown in Figure 2. The segments were made by adopting a fibre-reinforced mix based on a previous characterization campaign, where the optimization of the mechanical performance of the concrete reinforced with macro-polymer fibres was carried out. A mix design making use of blast furnace slag for the grading curve, following the Bolomey's law, was adopted: the proportions are given in Table 2. The mechanical performance obtained for this mixture was evaluated by uniaxial compression tests on four 150 mm side cubes and three points bending tests on prismatic beam specimens according to EN 14651. The results are presented in Tables 3 and 4. Based on this mechanical characterization, the mix used can be classified as C40/50 - 2.0e following the classification proposed by Model Code 2010 [8-11]. The properties of the polymer fiber manufacturer specified and used in the experimental campaign are shown in Table 5.

The first load test carried out is the 3-point bending test, performed on the tunnel segment at 7 days of natural aging in the laboratory. The curing time is equivalent to that obtained after a thermal cycle of 12 hours as usually adopted in the production.

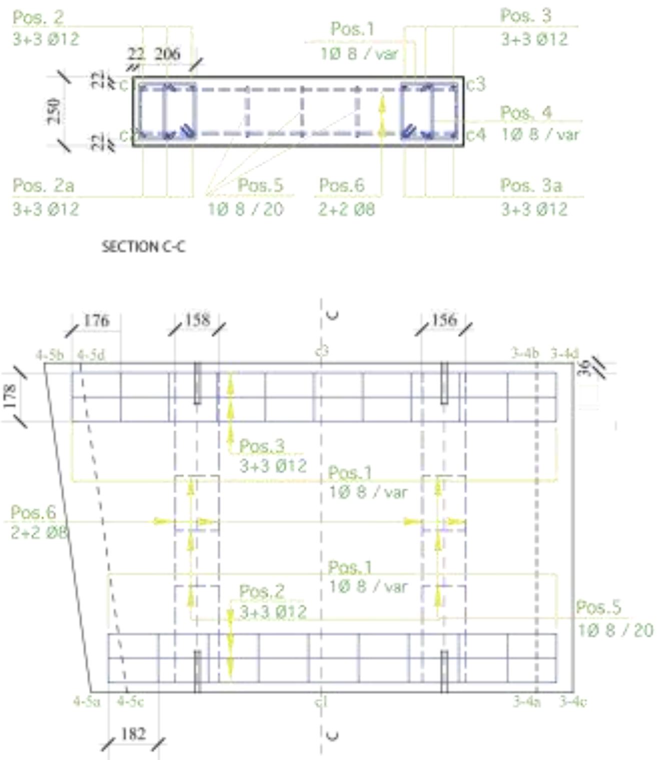

Fig. 2 *Minimum reinforcement introduced in the tunnel segment investigated.*

Table 3 *Concrete compressive strength*

N°	Density	$f_{cc,34}$ [MPa]	$f_{cc,M}$ [MPa]
1	2.314	65.90	**65.01**
2	2.302	64.00	
3	2.306	65.91	
4	2.290	64.22	

Table 4 *Flexural strength according to EN14651*

TEST	$f_{ct,L}$ [MPa]	$f_{R,1}$ [MPa]	$f_{R,2}$ [MPa]	$f_{R,3}$ [MPa]	$f_{R,4}$ [MPa]	Curing [gg]
1	3.72	2.56	3.49	3.99	3.91	7
2	4.21	2.72	3.08	3.56	3.75	
3	4.40	2.42	3.20	3.54	3.47	
Av.	**4.11**	**2.57**	**3.26**	**3.70**	**3.71**	
4	4.79	2.54	3.54	3.92	3.54	34
5	4.54	2.68	3.65	4.30	4.22	
6	5.37	2.87	3.53	4.03	4.04	
Av.	**4.90**	**2.69**	**3.57**	**4.08**	**3.93**	

The tests aim is to verify the behaviour and the bearing capacity of the fibre-reinforced segment in transient phases of handling and jack pushing during its positioning in the ring lining.

The three point bending test was performed using the set-up shown in Figure 3a. The structure, suitably instrumented at the intrados (Figure 4), was supported on two cylindrical supports spaced 1200 mm and the load was applied in the mid-section through the two plates placed on the extrados of the segment at a distance of 500 mm (Figure 3b). The crack was measured with the aid of a grid mesh of 100 x 100 mm drawn at the intrados of the segment as shown in Figure 4.

The compressive load test in the mean plane was performed at 34 days of ageing. The reference of the test was the TBM used for the construction of the hydroelectric tunnel Pando in Panama, equipped with 12 hydraulic jacks each of which with a load capacity of 785 kN in operating conditions and a load equal to 1175 kN in conditions of exceptional thrust. As the ring which forms the coating of the tunnel is formed by six elements, during the advancement of the machine each segment is subject to boost of 2 cylinders having a wheelbase of 840 mm, equal to the distance between the longitudinal connectors connecting the rings, and each provided with a shoe with a size of 195 x 510 x 450 mm (Figure 5c).

The test set-up used is shown in Figure 5. The jack couple is equipped with a single cylinder to the shoe: a layer of Teflon having a thickness of 35 mm was interposed between the load plates and the segment surface (Figure 5b).

The element has been suitably instrumented at the intrados and extrados, in order to measure displacement and crack opening close to the loading area.
The compression test was carried out following three different load cycles:
1. a cycle monotonic loading up to 1175 kN, consisting in several steps: a first cycle up to 100 kN; a second step with the load ranging from 0 to 785 kN (nominal thrust of the TBM in operation); a third load step from 785 to 1175 kN which corresponding to the maximum thrust of the TBM in exceptional condition;
2. an unloading from 1175kN to 0 kN;
3. a reloading cycle from 0 to 4000 kN (max thrust. of the loading device).

4. Experimental results

The 3-point bending test was carried out on a segment at 7 days of ageing: in Figure 6 the load vs. the crack opening measured in the mid-section is shown. Note that for crack opening of about 1.5 mm, the average comes to coincide with the recording of a single instrument because of the loss of a measuring instrument. From the results of the bending test it is possible to observe that the maximum bearing capacity is reached in the post-cracked phase. The ductile behaviour of the tunnel segment is highlighted by the following phenomena: the bearing capacity of the element continues to increase even in the proximity of the cracking onset, even in the presence of a minimum reinforcement; - the bearing capacity of the element continues to grow with increasing opening until opening values at ultimate limit state equal to 3.5 mm.

(a) (b)

Fig. 3 *Bending tests: (a) set-up and (b) scheme*

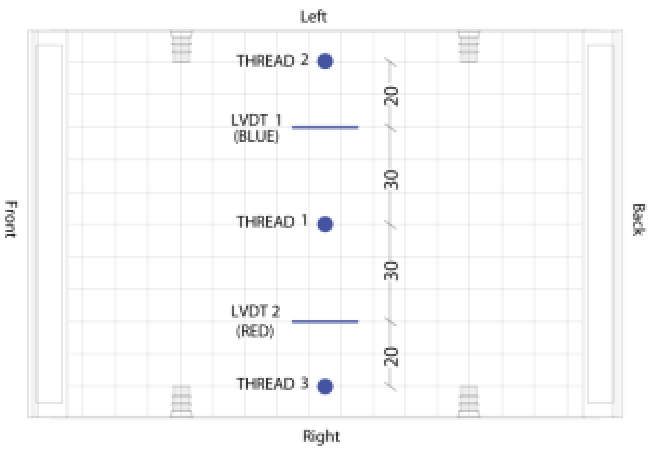

Fig. 4 *Segment instrumentation and representation of the grid mesh*

Table 5 *Fibre properties of ISTRICE 39/0.78*

Typology	Polymeric fibers for structural use (iBeton)
Composition	Compound of polymeric matrix with high density
Appaerance	Monofilamen
Diameter [mm]	0.78
Length [mm]	39
Specific gravity [kg/dm^3]	1
Ultim. tensile strength [MPa]	470
Elastic modulus [MPa]	3.6
Water absorption	None
Acids resistance	Total
Surface treatment	None

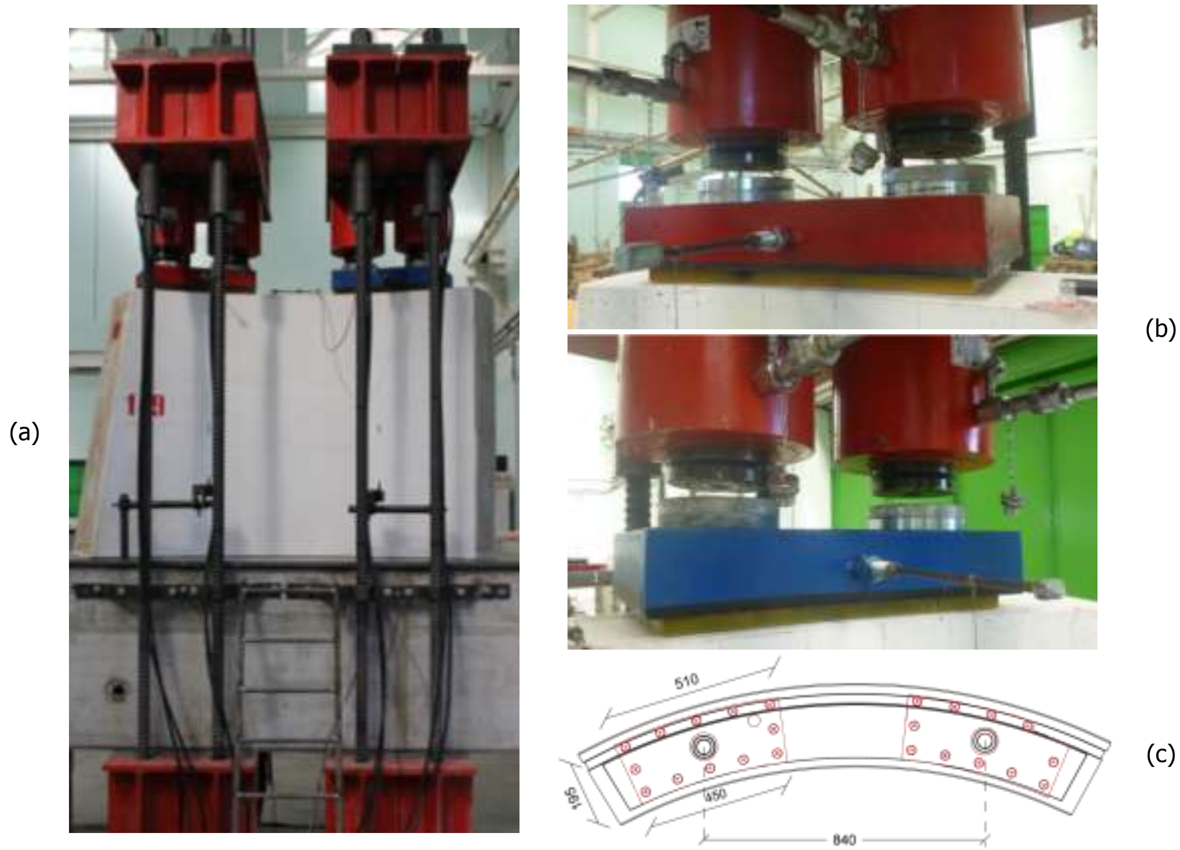

Fig. 5 *Compression test set-up (a) and load system details (b,c)*

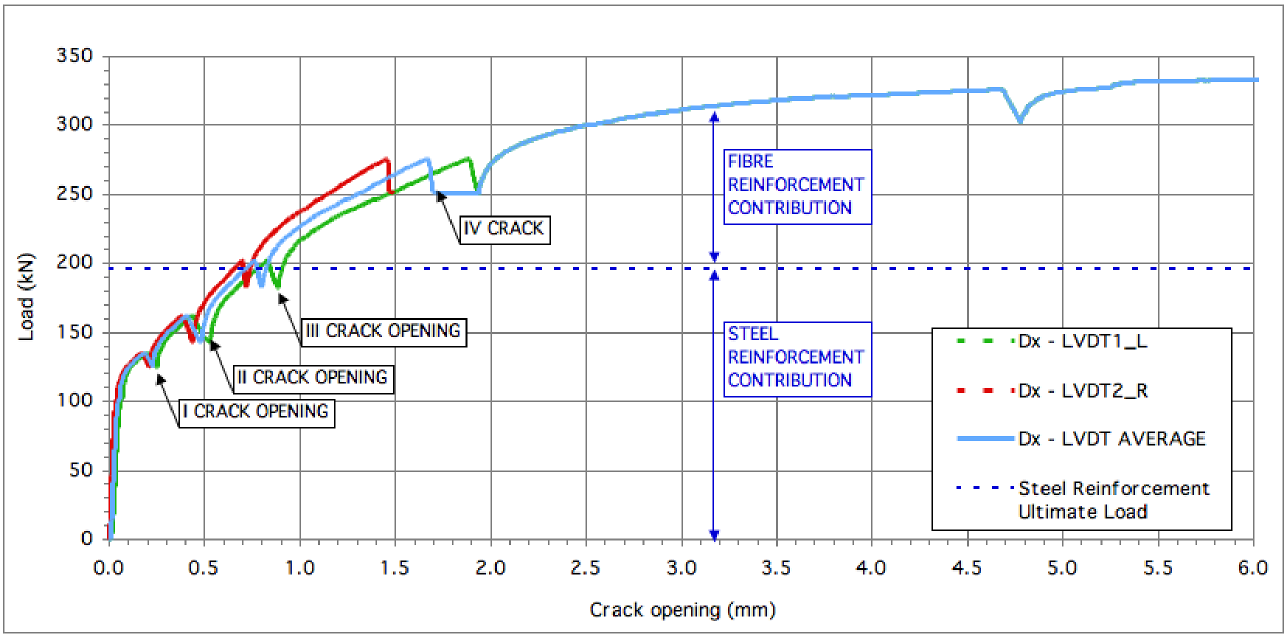

Fig. 6 *Load – average crack opening diagram: bending test*

The hardening behaviour evidenced emphasizes the coupling of 12 kg/m^3 polymeric fibres with a minimum reinforcement ensuring the ductile behaviour with large post-cracking resources, able to prevent the propagation of unstable fracture. Analysing the crack pattern observed during the test, it is worth to note that:

- at a load value of about 135 kN, a first crack propagates at the intrados of the segment in correspondence to the middle section and along the two lateral sides of the element, propagating toward the extrados. Its amplitude is still being negligible w < 0.05 mm;

- increasing the load up to 325 kN, a significant multi-cracking phenomena occurs, concentrated especially in the areas of the two lateral reinforced chords. The first crack continues to open, propagating towards the extrados, while new cracks open in the edges of the element at a spacing of about 15 cm, with a larger concentration in the middle section at the intrados, where the first crack formed;
- after the peak load of 325 kN, the element tends to open in two parts separating along the main crack formed at the intrados (Figure 7).

From the observation of the failure modes of the segment, at the end of the bending test it can be observed:

- a good distribution of fibres within the element, highlighted along the open cracks where a nearly constant number of fibres can be seen;

- a good interaction between fibres and matrix, since the greater number of fibres distributed along the crack presents a process of pull-out and not of premature rupture, guaranteeing the development of their full resistance capacity.

The compression test was performed on the segment at 34 days of ageing: the applied load versus the crack opening recorded at the intrados between the two shoes of the load is shown in Fig. 9. From the results obtained it is possible to observe that:

- the segment of the tunnel has a linear elastic behavior up to a load value of about 1000 kN, higher than the maximum load of the TBM under serviceability conditions and very close to the maximum thrust value in exceptional condition;

- the segment of the tunnel did not evidence a damage increase as a result of the cycle of unloading and reloading up to values equal to the maximum thrust of the TBM in exceptional condition. The slope of the unloading-reloading branch is the same as the elastic one and thus crack opening accumulated can be regarded as negligible;

- the crack opening measured by the LVDT placed between the two shoes is almost completely recovered at the end of the test, when the unloading of the element from the maximum value of 4000 kN is carried out; the crack opening decreases from 0.31 mm to 0.08 mm. The tunnel segment tends to close the crack up to a minimum value equal to the value of cracking observed for a load of the TBM of 1175 kN.

It is important to note that the crack opening was measured by the instrument relative to a single crack, in particular to the first crack formed between the two shoes during the first load cycle. Then cracks propagated outside the base of the instrument and therefore were not recognizable directly by the LVDT measure, but were measured manually using the crack measure device based on a visual inspection. From the evolution of the crack detected during the unloading and reloading cycles, the following remarks can be underlined:

- the slope of the unloading-reloading branch is the same as presented by the first elastic stretch during the first load cycle;

- at a compressive load of 1175 kN, the crack opening detected is the same measured at the first load cycle (w <0.05 mm).

- At a compressive load of 2000 kN a second crack at the intrados formed, between the two loading plates, propagation towards the right shoe load. This crack propagated parallel to the first, but for this load value still did not reach the upper surface of the element. The two cracks have a distance of about 15 cm and have approximately the same width (w <0.05mm).

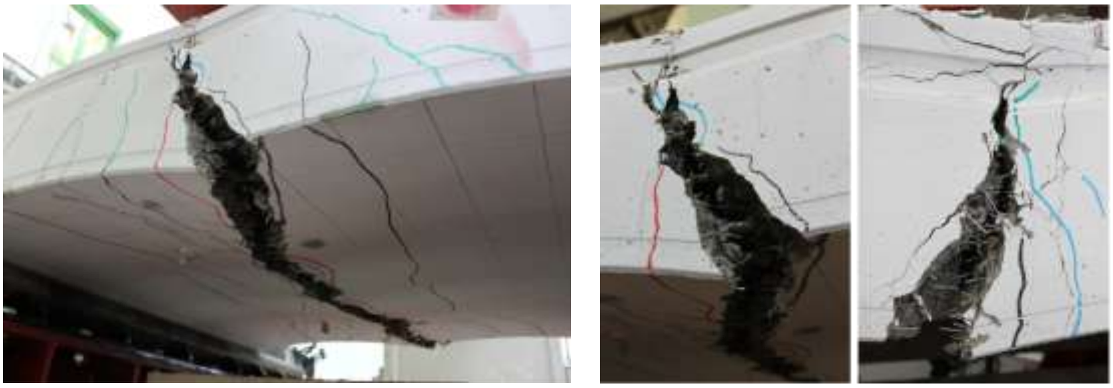

Fig. 7 *Crack openings at the end of the bending test*

Fig. 8 *Cracking pattern at the end of the compression test*

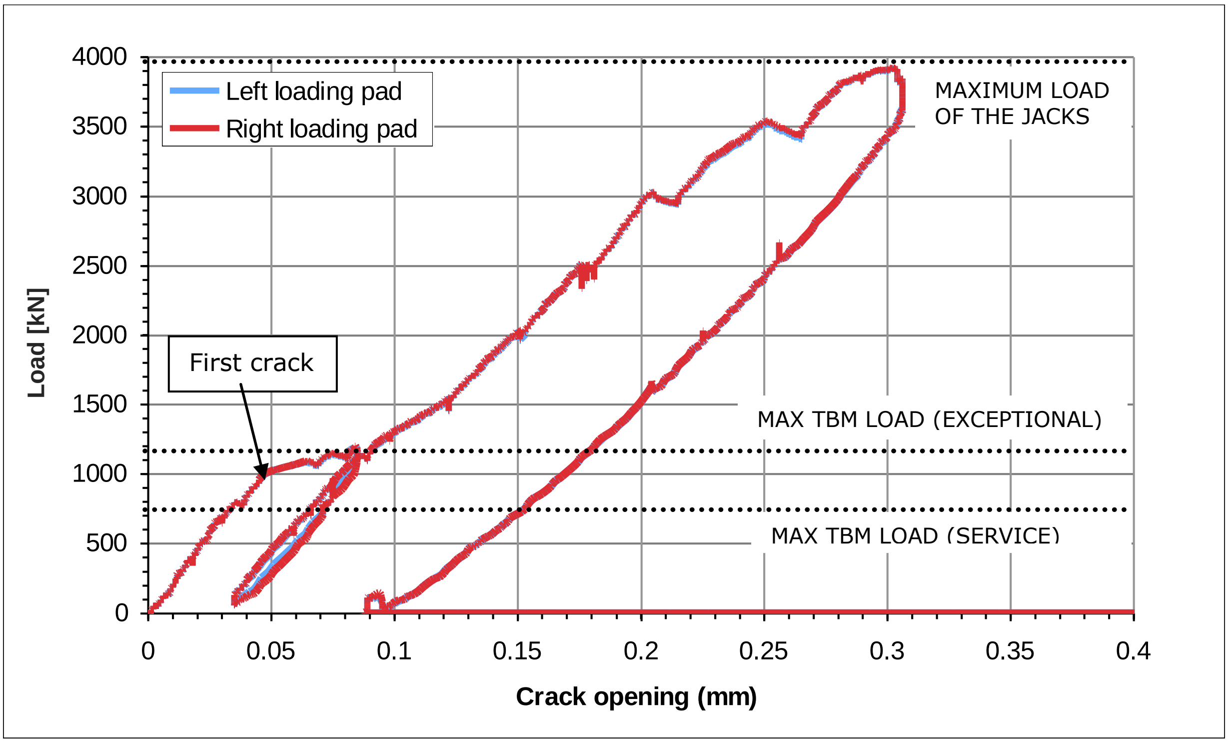

Fig. 9 *Load vs. crack opening*

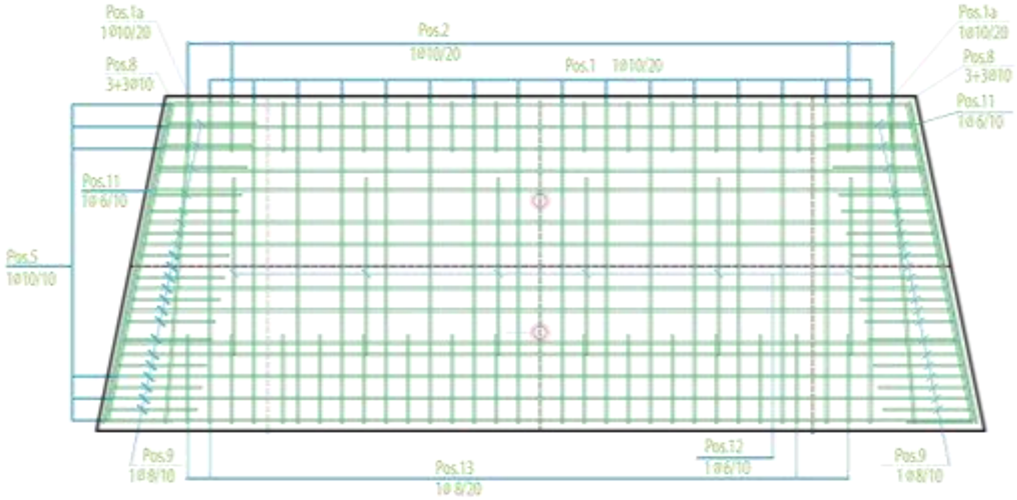

Fig. 10 *Tunnel segment traditionally reinforced (110 kg/m3 of steel reinforcement)*

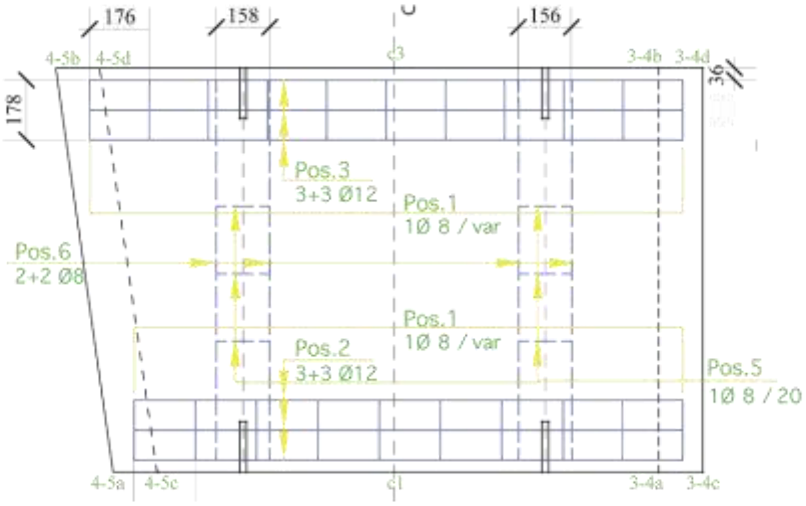

Fig.11 *Tunnel segment in fibre reinforced concrete (40 kg/m3 of steel reinforcement)*

Table 6 *Economic comparison between the proposed solutions*

FEATURES	**Traditional solution**	**FRC solution**
Concrete class	C45/50	C45/50, 2.0e
Steel reinforcement	110 kg/m^3	40 kg/m^3
Fibres	-	12 kg/m^3 polymeric fibres iBeton 39/0.78

- For a load of 2000 kN, the formation of a crack in correspondence of the element support, in line with the right side plate of the load was also observed. This crack propagated at both the intrados, and the extrados with a negligible crack opening (0.05 mm), visually identified and measured with the aid of a suitable manual device. For a load of 2500 kN, the two cracks in the proximity of the loaded area continued to propagate toward the centre of the element, along both surfaces of extrados and intrados, presenting a maximum opening of 0.1mm;

- for a load of 3000 kN, new bursting cracks appeared both in the central area of the intrados and at the extrados. These propagated perpendicularly to the tensile stresses due to the deviation of the compression flows resulting from the distribution of the stresses in the neck of the bottle. The other cracks had an opening in the range of 0.15 - 0.2 mm;

- for a load of 3500 kN the propagation of both the vertical cracks in the centre of the element took place with opening values w < 0.2 mm;
- for a value of compressive force of 3850 kN, corresponding to the maximum load of the jacks, the maximum opening between the cracks on the surface of the load between the two plates had a value of 0.35 mm and was recognized next to the left plate outside the measurement base of the LVDT. The same amplitude value was measured for the vertical cracks below the load plates, in the central area of the element.
- on the basis of market prices, the economic comparison shows a saving of around 45% in favour of the solution made of FRC.

The crack pattern detected at the end of the test is shown in Figure 8.

5. Conclusions

An experimental campaign on two tunnel segments, 250 mm thick, 1200 mm wide and 1700 mm long, made of a concrete class C45/50 - 2.0e according to model Code 2010 was performed. The classification was obtained using 12 kg/m^3 of polypropylene fibres 39/0.78 in combination with a minimum reinforcement arranged along two longitudinal chords consisting in 6 + 6☐12. The tunnel segment showed a ductile behaviour and was able to prevent any unstable crack development both in relation to bending actions resulting from the handling of segment in the first days of its life as well as to compression forces exerted by the TBM jackets in the segment plane. During the stages of lifting and transport at 7 days of ageing, the bending test highlighted a high post-cracking load-bearing capacity. In particular, the bearing capacity of the element continues to grow not only after the first crack, but also at the ULS; the bearing capacity of the segment continues to grow despite the spread of cracking, even for values of crack opening of 3.5 mm, i.e. at the ULS; along both the element chords a multi-cracking phenomenon was observed with a crack spacing not uniform in the cross section as expected, due to a reinforcement ratio not uniform in the cross section; the element tends to open in two parts along the first longitudinal crack opened in the middle section for load values equal to 325 kN.

The results of the compression test in the plane confirmed: an elastic behaviour until the maximum thrust value of the TBM under serviceability conditions; a single negligible crack opening (w <0.05 mm) for the maximum thrust value of the TBM in exceptional condition; a ductile behaviour up to a value of about 4000 kN of thrust applied through two plates of steel load of dimensions 195 x 510 x 450 mm. Moreover, during the load tests a good distribution of the fibres within the element as well as a good interaction of the fibres with the matrix could be observed, since most of the fibres developed a pull-out behaviour without incurring in a premature failure.

A comparison of a typical solution traditionally reinforced and the solution fibre-reinforced, coupled with a minimum quantity of reinforcement (Table 6) highlights a significant saving in terms of cost.

References

[1] Blom, C. (2002): Design philosophy of concrete linings for tunnels in soft soil. PhD Thesis, Delft University of Technology

[2] Blom, C., van der Horst, E. and Jovanovic, P. (1999): Three–dimensional structural analyses of the shield–driven "green heart" tunnel of the high–speed line south. Tunneling and Underground Space Technology, 14, 217-224.

[3] Tiberti, G. (2009): Concrete tunnel segments with combined traditional and fiber reinforcement: optimization of the structural behaviour and design aspects. PhD Thesis, University of Brescia.

[4] Cavalaro, S., Blom, C., Walraven, J. and Aguado A. (2011): Structural analysis of contact deficiencies in segmented lining. Tunnelling and Underground Space Technology, 26, 734-749.

[5] Caratelli, A., Meda, A., Rinaldi, Z. Design according to MC2010 of a fibre-reinforced concrete tunnel in Monte Lirio, Panama, 2012

[6] Structural Concrete, 13 (3), 166-173.

[7] Caratelli, A., Meda, A., Rinaldi, Z., Romualdi, P. (2011). "Structural behaviour of precast tunnel segments in fiber reinforced concrete." Tunnelling and Underground Space Technology 26 (2), 284-291.

[8] Tiberti, G., Minelli, F., Plizzari, G. (2014) Reinforcement optimization of fiber reinforced concrete linings for conventional tunnels, Composites Part B: Engineering, 58, 199-207.

[9] Tiberti, G. and Plizzari, G. (2009), Parametric study on tunnel linings in fiber reinforced concrete combined with traditional reinforcement. In Safe Tunnelling for the City and for the Environment.

[10] De la Fuente, A., Pujadas, P., Blanco, A., Aguado, A. (2012). "Experiences in Barcelona with the use of fibres in segmental linings." Tunnelling and Underground Space Technology 27 (1), 60-71

[11] Kasper, T., Edvardsen, C., Wittneben, G., Neumann, D. (2008). Lining design for the district heating tunnel in Copenhagen with steel fibre reinforced concrete segments. Tunnelling and Underground Space Technology. 23 (5), 574-587.

[12] fib Bulletin 65 (2012), "Model Code 2010 - Final draft", Volume 1, 350 pages, ISBN 978-2-88394-105-2.

[13] fib Bulletin 66 (2012), Model Code 2010 - Final draft, Volume 2, 370 pages, ISBN 978-2-88394-106-9.

[14] di Prisco, M., Colombo, M., Dozio, D. (2013), Fibre-reinforced concrete in fib Model Code 2010: principles, models and test validation, Structural Concrete 14 (4), 342-361.

[15] di Prisco, M., Plizzari, G., Vandewalle, L. (2009), Fibre reinforced concrete: new design perspectives, Materials & Structures, 42(9), 1261-1281.